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The Use of X-ray Images for the Assessment of the State of Preservation of Strengthening Interventions on Wooden Structures

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ABSTRACT: The need to preserve and enhance the value of wooden structures - which account for a sizeable proportion of the historical building heritage, in the form of floor slabs and roofing structures - has promoted the study and fine-tuning of techniques for the rehabilitation of such structures. Since the basic goal is the preservation over time of the structural and material values of a building, in selecting the procedures, the technologies and the materials to be used, it is essential to ensure compatibility with the original characteristics of the artefact. Nowadays, a prevailing trend is to replace the damaged parts of wooden structures with prostheses in the same type of wood, whether solid or laminar, so as to guarantee better compatibility between the original parts and the replacement elements. For years, however, since the second half of the Seventies of the nineteenth century, deteriorated wooden parts - i.e., parts no longer able to perform their structural tasks - were often reinforced by fitting prostheses made of epoxy modified concrete and linking them to the rest of the structure by means of connecting elements in fibreglass or steel, which extended into the wood and were made integral with it by means of epoxy-based adhesives. The effectiveness of this method hinges on the degree of mutual collaboration between wood and the prosthesis that is achieved thanks to the bonding of the prosthesis to the wood and the strength of the connection between the bars and the wood. Since the earliest interventions of this type date back to about thirty years ago it was deemed worthwhile to develop non destructive test procedures that might supply reliable indications on the state of preservation of these strengthening works. This paper describes the initial results of a research project aimed at defining a non-destructive testing procedure for detecting possible discontinuities in the connection between the wood and the steel, or fibreglass, elements. After a series of laboratory tests designed to define ad hoc tools for the investigation, an in-situ testing campaign was conducted, at the Farnese Theatre of Parma and the Racconigi Castle (in the province of Cuneo), to assess the applicability of the methods identified.

1 FOREWORD

Wood is one of the materials used most widely in the construction of slabs and roofing structures of historical buildings. The growing number of restoration interventions performed on this architectural heritage calls for the identification and fine-tuning of appropriate intervention methods that, in addition to preserving architectural and formal aspects, are also able to safeguard the structural and material characteristics of these constructions.

In order to ensure the preservation of the structural and material values of a structure, the selection of type of intervention, technologies and materials employed must be compatible with the original characteristics of the elements to be restored.

2 THE STRENGTHENING OF WOODEN STRUCTURES

Intervention methods entailing the replacement of entire structures or a drastic alteration to their structural conception due to a modification in their original restraint conditions have been virtually abandoned nowadays and an attempt is being made to identify valid intervention methods for the strengthening of wooden structures, that might be able to meet both static-structural and historical-structural requirements.

The restoration and/or strengthening process generally uses reinforcing elements that are connected to the wooden mass in different ways and are designed to increase the strength of the structures when it proves necessary to restore the original capacity of the wood in as much as the structure has been subjected to deterioration phenomena or when the loading conditions have to be modified due to a change in the intended purpose of the architectural structure. In particular, the portions that are badly damaged and are no longer able to fulfill their structural tasks have to be replaced. At present, the intervention technique used most widely consists of replacing the damaged parts with prostheses of solid or laminar wood of the same quality as that of the original structure, in order to ensure optimal compatibility between the original elements and their replacements.

Until a few years ago, however, these consolidation interventions used prostheses made of epoxy-based concrete connected to the rest of the structure by means of fiberglass or steel bars made integral with the wood with epoxy-based adhesives. The effectiveness of this process basically depends on the degree of collaboration obtained between the wood and the prosthesis, as is ensured by gluing the prosthesis to the wood and by the bar/wood connection.

Since the earliest interventions of this type date back to about thirty years ago, it was deemed interesting and useful to try to identify a non-destructive testing method that would supply accurate indications on the current state of preservation. Within the framework of a research project conducted by the author at the Architectural School of the Politecnico di Torino, an ad hoc testing technique was developed: initially tested on specially produced laboratory specimens, it was subsequently applied directly on site to wooden structures of the Farnese Theatre of Parma and the Castle of Racconigi.

3 NON-DESTRUCTIVE TESTS FOR THE ASSESSMENT OF THE STATE OF PRESERVATION OF STRENGTHENING WORKS USING PROSTHESES IN EPOXY-BASED CONCRETE

3.1 Evaluation of the state of preservation of restoration works by means of the X-ray technique

The structural validity of strengthening works performed through the introduction of prostheses in epoxy-based concrete is strictly correlated with the existence of an effective collaboration between the wood and the prosthesis. Detachment phenomena between these two elements – as may be caused by differences in the behavior of these materials when exposed to variations in thermo-hygrometric conditions, or a lower degree of deformability of the epoxy-based concrete vs. wood – may leave the validity of the intervention unimpaired, as long as these phenomena do not give rise to significant discontinuities between the bar and the wood.

In order to evidence the presence of detachments, different methods have been evaluated by performing numerous tests on specimens with known characteristics. Ultrasound and thermographic tests proved unable to provide interesting results. Conversely, images produced by X-rays – a technique widely adopted to assess the state of preservation of metal elements and welded joints – were able to discern bars of different sizes in the wood and to identify the discontinuities along the bar/wood connections. The reduced absorption capacity of the air compared to the other materials, in fact, makes it possible to identify any discontinuities as may be present along the bar/wood connection: they are revealed by the presence of dark-colored zones adjacent to the unbounded bar portions, as observed in the X-rays taken on specimens specially prepared to this end.

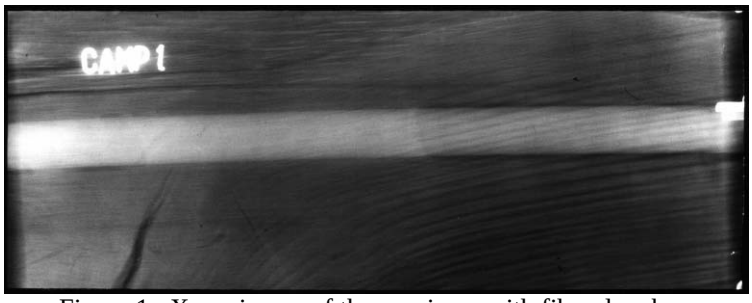

Figure 1 : X-ray image of the specimen with fibreglass bar.

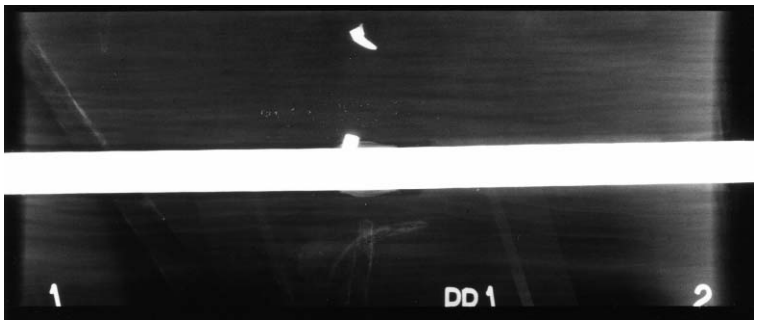

Figure 2 : X-ray image of the specimen with steel bar.

Having ascertained the effectiveness of X-ray tests in the laboratory and having determined the optimal exposure time, a series of tests was performed directly on site, on a rafter-ridge beam node in one of the trusses supporting the roofing of the Farnese Theatre of Parma and the roof structure of the central pavilion of the Castle of Racconigi (CN).

3.2 Evaluation of the state of preservation of the static strengthening of the trusses of the Farnese Theatre (Parma)

Constructed in 1618 by Gian Battista Aleotti for Renuccio I Farnese, the theatre has an ellipsoidal plan with thirteen wooden stairways topped by wooden loggias with pilasters of the Doric and Ionic orders. The roof structure is made up twenty wooden trusses spaced 1.35 m apart and spanning over 32.22 m.

Figure 3 : The Farnese Theatre of Parma.

The trusses are fitted with two stiffening elements consisting to a triple framework system with wooden rafters and iron braces plus a plain horizontal rafter inserted between two nodes of the aforementioned system. In 1981, the trusses, that had undergone several previous interven-

tions, were subjected to strengthening works prompted by the observation of significant deterioration conditions at one of the rafter-ridge beam nodes, due to the joint effects of humidity, moulds and wood-eating insects. Damaged wooden parts were removed and replaced with epoxy-based concrete prostheses and quartz aggregates, which were connected to the rafter -ridge beam node by means of fiberglass bars (20 mm in diameter) made integral with the wood by means of a 5 mm layer of epoxy paste.

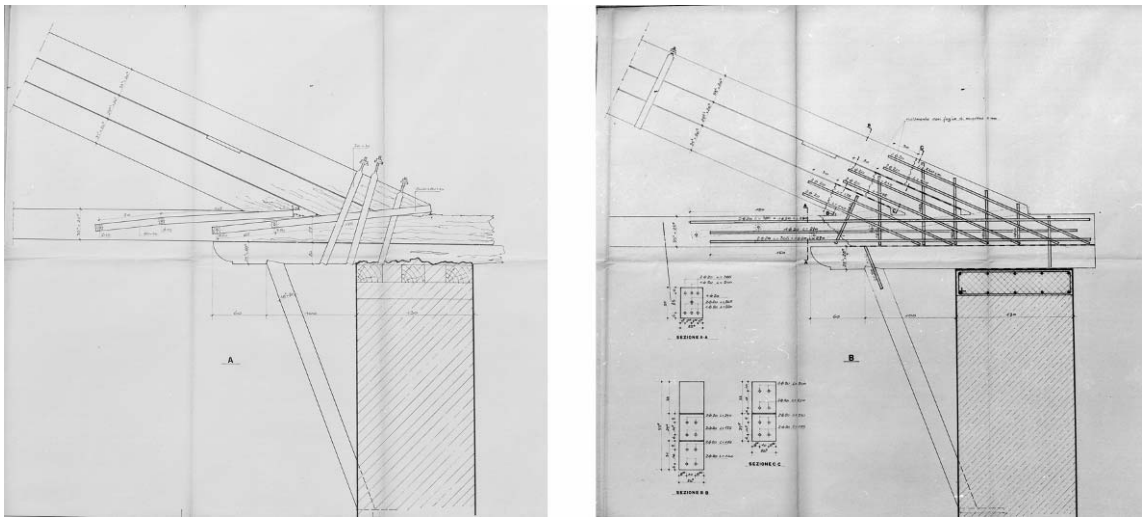

Figure 4 : Farnese Theatre, Parma. The strengthening intervention project (Architects Mariella De Cristofaro, Delio Fois).

In order to evaluate the current conditions of the trusses, tests were performed by means of type “Balteau 160” radiographic instrumentation, with a focal distance of 70 cm, 80 kV voltage and 5 mA current. The X-ray images – produced by the C.M.E. company of Albignasego (Padua) under the scientific supervision of the author – made it possible to ascertain the absence of discontinuities between the bars and the wood, since the images showed no dark-coloured areas along the bars.

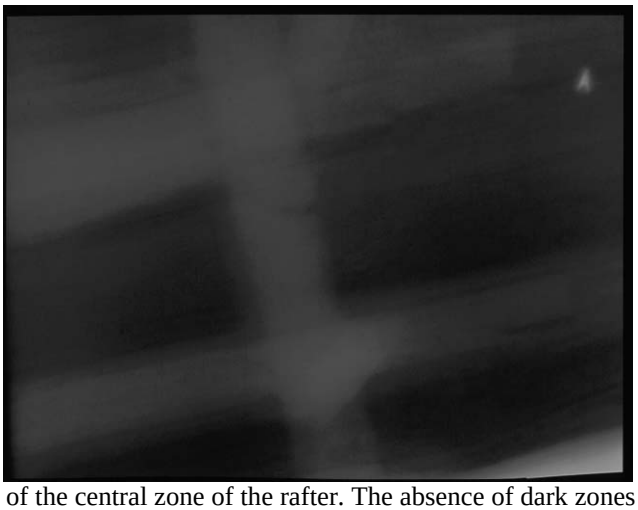

Figure 5 : X-ray image of the central zone of the rafter. The absence of dark zones around the bars shows that there are no discontinuities between the bars and the wood.

Figure 6 : The Castle of Racconigi (CN).

3.3 Evaluation of the state of preservation of the static strengthening of the trusses of the central pavilion of the Castle of Racconigi (CN)

The Castle of Racconigi, whose initial core dates back to the early eleventh century, underwent expansion works at the end of the seventeenth century. In 1675-76, Guarino Guarini, upon the request of Emanuel Filbert of Savoy-Carignano, produced an intervention project for the transformation of the castle «of clearly medieval design, with a square plan, towers at the four corners and an inner courtyard distributing access to the rooms» (Gonella 1987) into a structure integrated into the surrounding space. Guarini's design project envisaged the construction of a hall, in lieu of the original courtyard, which should have served as a «centre of attraction and irradiation for the entire structure» (Gonella 1987).

The roof of the emerging part of the central hall consists of a pagoda-like pavilion, whose bearing structure has five rather complex rafters, organized into three superimposed orders and spanning over approximately 13 m. These elements that can be likened to a mixed truss-frame system are characterized by the presence of three superimposed orders of ridge beams and queen posts and two orders of rafters and knee rafters. «In actual fact, they consist of a complex set of elements that elude an exact static definition, with geometric situations that are able to confer a certain stiffness to some nodes only» (Bertolini, 1992). In the course of the centuries, they have been subjected to numerous integration and strengthening interventions, which have altered to some extent the original structural conception.

In the 1980s, during the restoration works performed on the roofing of the castle, the Margheria complex and the greenhouses, static intervention works were performed on a number of trusses of the roof of the central pavilion.

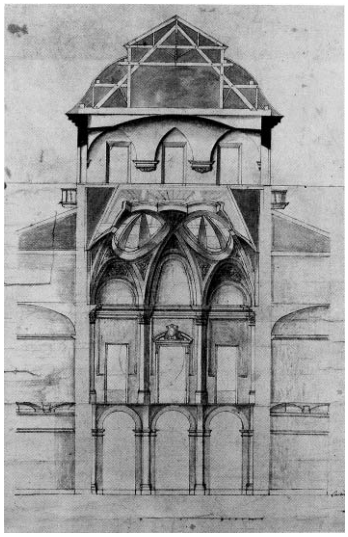

Figure 7 : Castle of Racconigi (CN). Cross-sectional view of the central hall and its roofing. Design project by Guarino Guarini (State Archives of Turin, Az. Savoia-Carignano, categ. 95, m. 2).

Conditions of severe deterioration having been observed at the wall supports of some ridge beams as well as some ridge beam-rafter and upright connecting nodes, caused by the combined action of moisture, moulds and wood-eating insects, it was deemed necessary to fit prostheses. Made with epoxy resin based concrete and quartz aggregates, these prostheses were linked to the wooden elements by means of fiberglass bars (20 and 24 in diameter), made integral with the wood by means of epoxy paste.

The state of repair of the strengthening elements was evaluated by means of radiographic tests, which, in this case too, were performed with a type “Balteau 160” X-ray unit, having a focal distance of 30 cm, 85 kV voltage and 5 mA current. Having completed a number of preliminary tests to identify the optimal exposure time, nine X-ray images were taken in a direction parallel to the longitudinal axis of the lower ridge beam of the truss most affected by the strengthening interventions.

From an examination of the radiographic images it proved possible to identify the positions of the fibreglass bars and to verify gluing conditions. In some cases, situations of discontinuity were observed in the connections between the bars and the wood, which – in all probability – should be ascribed to a non perfect execution of the strengthening intervention, whose static validity, however, was not impaired.

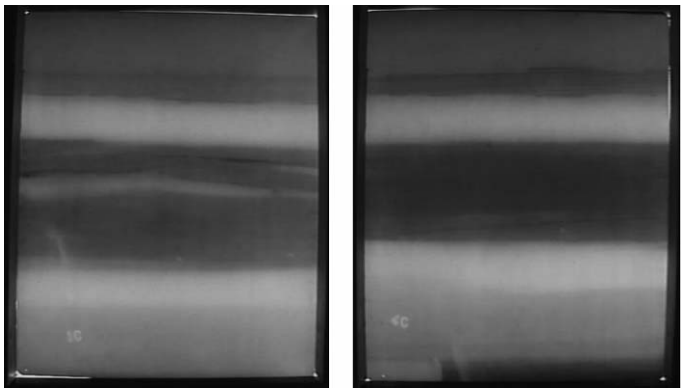

Figure 8 : Castle of Racconigi (CN). X-ray images of the portion of the ridge beam that has been subjected to the strengthening intervention. The darks areas around the upper bar evidence the presence of discontinuities between the bars and the wood.

4 CONCLUSIONS

The tests conducted so far have made it possible to ascertain the applicability and effectiveness of this testing method. The results obtained in the course of the testing campaign also suggest the wisdom of conducting these tests *in itinere* – during the installation of the prostheses – in order to verify the correct execution of the strengthening intervention underway.

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